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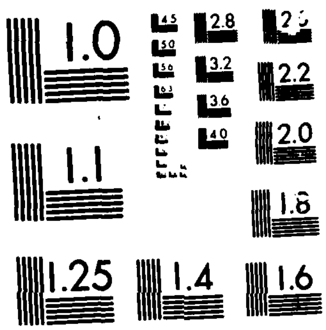

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EVALUATION OF THE USE OF HYDROGEN-OXYGEN AS A BREATHING GAS IN DEEP-SEA DIVING

By

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EVALUATION OF THE USE OF HYDROGEN-OXYGEN AS A BREATHING GAS IN DEEP-SEA DIVING

ABSTRACT

This study attempts to define the state-of-the-art for the use of Hydrogen-Oxygen mixtures for diving operations by compiling information relative to past and current research efforts in the U. S. and foreign countries. This information was utilized to indicate possible areas of application with this mixture for appropriate conditions and define areas in which hydrogen-oxygen mixtures could offer physiological advantages not possible with currently used breathing mixtures. Further research requirements prior to operational use of this mixture are indicated from this study and recommendations for current and future research and development needs are included in this report.

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BACKGROUND

Manned dives with air have been conducted for over 300 years and today, because of simplicity of operation, air is still the most utilized breathing, mixture for underwater operations at the lower pressures.

Unfortunately the Narcotic properties of Nitrogen prevent application of air and/or nitrogen-oxygen mixtures at depths significantly greater than 200 FSW (Feet Sea Water). For greater depths Helium-Oxygen mixtures are normally used since thses mixtures do not produce narcosis in humans at high pressures. However, at higher pressures, Helium was discovered to produce HPNS (High Pressure Nervous Syndrome), Bennett (1). This effect can render the diver ineffective at very high pressures (beyond 1000 FSW). HPNS problems may be minimized to some extent by pressurization of the diver at a very slow rate and/or the addition of nitrogen to the mixture to offset the HPNS effect, Bennett(2). In the latter case the breathing resistance is increased to very high levels for a working diver and at some point this factor would inpose a physiological limitation. Even without the addition of nitrogen, the high breathing resistance levels could preclude any significant activity on the part of the diver at very high pressures.

Helium is not the only inert gas which may be utilized for dives beyond 300 FSW. Neon and Hydrogen also can be employed for deep diving operations, Edel(3). In the case of Neon, the molecular weight (and breathing resistance) is even greater than that for helium and the limitations that would apply to helium in mixtures have been used in human experiments over 40 years ago by Case and Haldane (4) for brief chamber exposures and later in open water dives as deep as 520 FSW by Zetterstom of Sweden reported by Bjurstedt and Severin (5). Chamber experiments by Edel (6,7) for long exposures showed no contra-indication of its use as diving mixture and indeed pulmonary function measurements made during these tests showed that the breathing resistance of a 97%H_2-3%O_2 mixture to be 50% of that of a 97%He-3%O_2 mixture at 200 FSW, Dougherty (8). Recent human experiments by Comex showed hydrogen to have one fourth the narcotic properties of nitrogen, Fructus (9). Hence dives with hydrogen-oxygen mixtures might be possible as deep as 750 FSW. This is about 150 feet below the accepted practi al limit of 600 FSW for "bounce dives". Deeper dives might be performed with a helium-hydrogen-oxygen mixture in which the narcotic properties of hydrogen would counterbalance the HPNS properties of helium and still result in a lower breathing resistance than if helium-oxygen alone were utilized. Such a mixture could greatly extend the maximum achievable depth range for commercial and military driving operations.

METHOD

A literature review was conducted and visits made to the sites of the Swedish National Defence Research Institute and Comex Laboratory where the most recent hydrogen-oxygen experiments have been made. Data from these experiments, as from earlier efforts, were compared. Where available, decompression and counter diffusion data were analyzed using the Autodec system for decompression analysis.

HYPERBARIC APPLICATION OF HYDROGEN-OXYGEN BREATHING MIXTURES IN RECENT HISTORY

The earliest animal exposure was reported by Lazarev (10) in 1941. In this experiment, a mouse was exposed to a maximum pressure of 90 atm. during a two hour exposure. Due to the war, pure hydrogen was not available and the only gas at his disposal had, what he referred to as, a sufficient quantity of carbon monoxide to "form a toxic concentration of carbon monoxide" at high pressure. As a result, he diluted the gas by adding nitrogen to the chamber during pressurization. At 90 atm., the gas mixture was 55 atm. hydrogen, 33.25 atm. nitrogen and 1.75 atm. oxygen. The survival of the animal from this exposure undoubtedly offered encouragement to later experimenters.

In the same year, Case and Haldane (4) made a brief exposure with hydrogen-oxygen at 300 FSW in a dry chamber without reported difficulty.

Shortly after the above experiments, Arne Zetterstrom made a series of open water dives using hydrogen-oxygen which were reported in 1948 by Bjurstedt and Severin (5). In this dive series Zetterstrom reached a depth of 160 meters in his last dive. Unfortunately, due to an error he was brought directly to the surface from a 20 minute exposure at 160 meters, without any decompression stops, which resulted in his death. Although the death was not a result of the breathing mixture per se, it had the result of discouraging further experiments with hydrogen-oxygen for some time thereafter.

One of the problems he had to contend with using hydrogen is the wide range of explosive and/or flammable ratios with oxygen. Percentages of oxygen which would be non-explosive and non-flammable do not provide a sufficient oxygen partial pressure at sea-level to be utilized. He solved this by using air to descend to about 5 ata. At that depth he would shift briefly to a mixture of 96%N_2-4%O_2 (to flush the lines) and then to the mixture (in his later dives) of 96% H_2-4% O_2, before continuing his descend. On the return, the procedure was reversed.

While performing the experiment in the open water provided the opportunity to use a total systems approach which would be similar to that which might later be applied operationally, it had the disadvantage of not permitting the detailed physiological experiments which could be performed in a dry chamber. It was noted, however, that the divers voice was "nasal and indistinct" and morse code was used to permit the diver to communicate with the surface. At the maximum depth of his last dive, Zetterstrom reported no subjective symptoms of narcosis at 160 meters and that inhalation resistance seemed to him to be equivalent to 40 meters with air. On an earlier dive, he also noted the low inhalation resistace noticed with the hydrogen-oxygen mixture and felt the low temperature of the water sooner, as a result of the high heat conductivity of the hydrogen gas. Preheating of the gas was therefore recommended.

The major portion of the Bjurstedt and Severin paper (5) dealt with the background for the decompression computations and the discription of the theoretical model used. Considering the period, it involved some very advanced concepts. The method was used to develop what was probably the first tables constructed and tested based upon a model assuming different half-time values for different inerts in a given compartment. The total compartment gas loading was assumed to be the sum of the gas loading for each of the inerts (in this case nitrogen and hydrogen) used in the experiment. Using this concept both multi-inert mixtures (N2 & H2) and sequential shifting of inerts were utilized in the dive series. Since safe utilization of hydrogen as an oxygen diluent requires other inert-oxygen mixtures to be utilized at shallower depths a decompression model capable of handling several inerts to be utilized on a single exposure was a vital necessity.

In the late 1960's Brauer (11,12) exposed mice and squirrel monkeys to mixtures of He/H2/02 at pressures of 60 to 90 ATA for periods as long as 24 hours and was able to conclude that these pressures could be tolerated without "dramatic evidence of damage" even after considerable periods of exposure. As a result of his experiments he also concluded that hydrogen was approximately 1/4 as narcotic as nitrogen. This appears to be confirmed in recent human experiments.

In that same general time period, Edel (13) made a series of hyperbaric exposures with hydrogen-oxygen in a dry chamber at a depth of 200 FSW. The initial dives, for duration of 10 and 20 minutes, were utilized to test the system for handling these mixtures in the operational system designed for subsequent experiments. Although the decompression procedures were considered to be conservatively based upon any inert which would have characteristics between those of nitrogen and helium for the faster tissue compartments, and the subject's general susceptability to decompression sickness had been well established in many previous dives with other inerts, minor decompression sickness problems were encountered in the 2nd dive with an exposure time of 20 minutes. Although this involved only a single subject, the individual's base susceptability to decompression sickness had been well established in previous hyperbaric exposures involving both symptomatic and asymptomatic responses to various decompression schedules. A retrospective analysis of this dive using the Autodec III system indicated an unusual sensitivity with hydrogen with respect to the faster tissue compartments in comparison with established criteria for the slower tissue compartments with hydrogen.

Subsequent exposures involved experiments made at the same pressure with exposure times of 30 minutes to 2 hours without problems

(Edel and Fife (7)). In addition, dogs were exposed to pressures of up to 31 ATA for periods of up to 39 hours. The animals appeared to tolerate this exposure and did not subsequently show any sign of pathological symptoms. In addition, variations of the chamber temperature with both helium-oxygen and hydrogen-oxygen indicated (based upon the response of the animals) no difference in the optimum temperature setting for comfort with either mixture.

Fife (14) carried out a number of additional experiments on dogs, rats and mice at pressures of up to 305 meters, with biochemical and histological examinations carried out on the dogs. As a result of his studies he concluded that hydrogen was innocuous for animals for depths up to 300 meters. Additional experiments were made for short durations with humans breathing hydrogen-oxygen to depths of 300 FSW. Some decompression problems resulted from these exposures which involved fast tissue compartments.

Later experiments by Edel (15) were carried out with subjects exposed to normoxic mixtures of Hydrogen-oxygen, helium-oxygen, and nitrogen-oxygen (in separate exposures) using the same subjects. The dry chamber dives were conducted at a depth of 200 FSW for period of 120 minutes. As a result of these studies, Edel determined that the half-time for hydrogen in the slowest tissue compartment was approximately 1.5 times that for helium and .75 times that for nitrogen.

Tests did not reveal any signs of narcosis with hydrogen at this pressure and the speech intelligence level appeared to be slightly better for hydrogen than for helium, Seargent (16). Pulmonary function measurements indicated a 50% reduction of breathing resistance at that pressure, for hydrogen as compared with helium, Dougherty, (8).

In that time period also, Comex exposed a Papio papio baboon to hydrogen-oxygen for 1/2 to 2 hours at pressure of 200 to 675 meters. The shallow exposures were uneventful. The animal developed severe HPNS symptoms at 675 meters which were readily reversible upon reduction of pressure, Rostain & Naquent (17).

In that same time period, Michaud, et al. (18) exposed 5 rabbits to hydrogen-oxygen to 29 ATA for several hours at preselected temperatures. The animals developed a toxic syndrome and died.

The experiments were later reproduced by Ornhagen, et al, (19) with 12 rabbits exposed to 30 ATA of hydrox for time periods of 24 to 48 hours without any evidence of harmful effects. Additional experiments involved shorter animal exposures to 60 ATA which were likewise innocuous.

Additional studies were carried out by Comex (20) on mice for exposures of 42 hours at 600 meters. No discernable pathological, funtional or organic reactions were found. Later eight exposures of humans in open water dives were made with hydrogen-oxygen (for 5 minute breathing periods on that mixture) at depths of 70 to 91 meters. There were no problems encountered in that dive series but it was noted that the decompression stops were deeper and approximately 30% longer than would be required by helium-oxygen tables.

In the last two years, 3 human experiments have drastically increased our knowledge of hydrogen-oxygen mixtures at high pressures.

The Swedish National Defence Research Institute experiment Project Hydrox A involved the first human exposures to hydrogen-oxygen in that country since the Zetterstrom dives. As reported by Orhagen (21) the chamber was initially flushed via a compression/decompression phase whith helium to remove unwanted nitrogen (which could affect later narcosis measurements) before the men were compressed to 120 meters with a helium-oxygen saturation exposure upon which hydrogen-oxygen breathing periods were superimposed.

The results of narcosis tests reported by Adolfson, et al (22) showed no noticeable change in visual reaction time with heliox or hydrox at 1.3 MPA. Neither were any tendencies of increased body sway noted in standing steadiness studies. However, the paced auditory serial adition tests indicated a tendency to deterioation in all three divers. Perhaps of equal interest is the one divers comment that comparison between H2 narcosis and N2 narcosis is like "the difference between valium and home made wine".

Dahlback (23) reported a 35% lower functional lung resistance with hydrox as compared with heliox and a MVV during hydrox breathing 26% higher than the corresponding value for heliox.

In workload studies, Gennser, et al (24), no significant difference between gases was noted. Doppler monitoring and absence of symptomatic response, as reported by Brubakk, et al (25), revealed no signs of bubble formation of decompression sickness as a result of counter diffusion problems.

The Hydra IV was performed by COMEX in November of 1983. As in the Swedish experiment, the hydrogen breathing was superimposed upon a helium-oxygen saturation proiile with a maximum depth of 300 meters with

In the Comex experiment, however, the system permitted wet pot exposures with hydrox and heliox breathing periods made at 120, 180, 240 and 300 meters to permit comparison of the effects of the mixture at different pressures. In addition, mixtures of hydrogen- helium-oxygen were used at the maximum pressure of 300 meters.

The chamber system was also preflushed with helium to remove nitrogen from the chamber prior to compression on helium-oxygen.

Narcosis studies, Fructus, et al (9) and Carlioz, et al (26) showed very slight effects with hydrogen at 120 meters. At 180 meters, the narcosis was more definite but still very slight and not incapacitating. At 240 meters, the narcosis was more pronounced and probably beyond the limit that could be considered acceptable for normal operational use. Again the mathematical test (multiplication test) was the most sensitive in indicating a performance decrement. The use of the tri-mix (containing 74% H2) at 300 meters produced barely perceptible narcosis in the subjects.

Again the difference in the character of narcosis between hydrogen and nitrogen is mentioned repeatedly. In the early stages divers considered hydrogen narcosis to have hallucinogenic effects.

Noted was a hypoventilation effect at 240 meters which might suggest slower elimination and thus retention of carbon dioxide.

At 240 meters, on hydrogen, a respiratory depressant effect was definately observed on one diver which was reversible upon switching the subject to the helium oxygen mixture.

Isobaric counter diffusion was indicated on several occasions. After a return to a helium-oxygen breathing mixture following short duration hydrox breathing exposures, very low bubble flows were detected. However, after a four hour exposure with hydrox at 150 meters one diver exhibited high grade bubbles for a long time. This individual was previously noted as a "bubble producing subject" from previous experiments. Interestingly, another diver in the series (also noted as a "bubble producer" in a previous experimental dive series exhibited no bubbles after a 6 hour exposure to hydrox, Masural, et al (27).

HYDRA V was conducted in the Comex laboratories to a depth of 450 meters. Trimixes (H2/He/O2) were utilized as the saturation gas mixture in the chamber, Fructus (28).

The initial results indicated a definite increase in the divers work output with hydrogen-helium-mixtures as opposed to helium-oxygen. In addition, the ability to provide a balanced mixture in which the narcotic properties of hydrogen could be utilized with helium to counter the HPNS effect was well demonstrated. The difficulty in making a shift from the trimix to a helium-oxygen mixture in two equal stages of reduction of the hydrogen partial pressure resulted in definite counter-diffusion problems which required compression to a greater pressure for therapeutic reasons. The symptoms were reported after the second switch (from 50% of the hydrogen percentage in the bottom mixture to a pure helium-oxygen mixture). However, the possibility of a supersaturation of gas resulting from the initial gas switch being exacerbated after the second gas switch can not be completely discounted. This problem was, however, eliminated in the decompression of the second team where the transition from a hydrogen-helium-oxygen atmosphere to a helium-oxygen atmosphere was made over a multi day period during the ascent.

FUTURE RESEARCH

Both Swedish and French scientists are hopeful that the research efforts can be continued in the future. In a recent talk Henri Delause, President of Comex (29) stated that he hopes to be able to use hydrogen-oxygen commercially in the near future for deep diving. This would be especially beneficial in some areas where helium supply problems create difficulty in maintaining continuous operations. The possibility of using hydrogen-oxygen diving from Comex's SAGA-1 submarine, which would serve as a portable underwater base site for the divers was also mentioned.

As the next proposed future hydrox experiment by Comex would be at greater pressure, the scoupe of research conducted is planned to be similar to that of Hydra V. Past results may suggest increased interests in the areas of counter diffusion and narcosis/HPNS balance problems.

RECOMMENDED AREAS FOR FUTURE RESEARCH

Some thought must be given to basis for criteria to be applied for research requirements as a prerequisite for possible utilization of He-02 mixtures at a future time. A very strict approach which would exceed data base requirements for breathing mixtures already utilized would seem inappropriate and indeed prevent any future utilization of such a system within the foreseeable future. On the other hand, an acceptance of a research area as satisfactory on the basis of no contra-indications when the investigation has been superficial could permit a potentially hazardous area to remain uninvestigated.

The proposed criteria would take a middle view. If an area has been sufficiently investigated under appropriate conditions and has shown no contra-indication to utilization of the breathing mixture in question, (from both the physiological safety and the operational viewpoint) this area will not be identified as requiring further research prior to utilization of the mixture (even though there may be areas of academic interest which should be encouraged for further investigation apart from a "requirement prior to utilization").

One such example, (on a provisional basis) might be related to hydrogen speech. There are a number of reasons for investigating hydrogen speech characteristics from an academic viewpoint and indeed such research could lead to a better understanding of requirements for voice unscramblers. Yet if, as preliminary reports indicate, hydrogen speech is more intelligible than helium speech and existing helium unscramblers provide an intelligibility level with hydrogen-oxygen mixtures which is as good or better than speech from helium-oxygen mixtures, it would seem inappropriate to make further research in this area a prerequisite to use for hydrogen-oxygen.

To cover degrees of desirability between the extremes (research definitely required prior to utilization vs. no further research required prior to utilization) intermediate research priority levels would be applied to indicate a desirable (although not strictly essential) researc-h area, and areas which might logically be included in primary programs to obtain more data. Indicated research areas are identified as to recommendations for human or animal studies or both as applicable.

In potential utilization of hydrogen-oxygen mixtures in general there seems to be a sharp distinction between He-02 mixtures as such and He-He-02 mixtures. Significant differences exist in applied depth range, physiological problems, and operational application. This also results in a difference in research requirements prior to possible utilization. He-02 mixtures as such have a limited depth range. The minimum depth is determined by the percentage of oxygen in hydrogen which is safe with respect to flammability and explosive limits. In practice this would be between 150 and 300 FSW. A 97%H2-3%02 mixture, which appears to be somewhat conservative with respect to such limits, would provide a "normoxic" mixture at 200 FSW.

The upper limit would be determined by the narcosis limits which would appear to be about 600 FSW. This is also about the maximum practical depth in which a non-saturation dive m be made in which sufficient bottom time can be attained to permit the diver to achieve some limited tasks. Hence, a reasonable range for utilization of a pure hydrox mixture would be in the 200 to 600 FSW range. Ideally, such a system could be achieved with on-board generation of all the gas mixtures required, permitting the diving activity to be independant of gas supply problems. In this respect such a system would offer some advantages over helium-oxygen diving in which large supplies of gas must be maintained and re-supply of gas must be maintained from distant shore sites.

The H2/He/02 mixture still has the same minimum depth limits but may be applied over a much greater depth range, perhaps eventually as deep as 1000 meters. Yet the requirement for helium in the mixture adds an undesired complication with respect to supply problems. In addition, the percentages of the gas mixture may have to be varied in response to major depth variations to achieve a desired balance to avoid HPNS and narcosis problems while maintaining the lowest possible breathing resistance with respect to the narcosis/HPNS requirements. Since this mixture would tend to be more complex in terms of logistical considerations and technical control, as compared with a pure hydrox system, potential future applications with H2/He/02 mixture are more likely to be in a saturation type of system with application at greater than the absolute minimum possible depth.

This also results in a difference in research requirements prior to possible utilization. For example, utilization of a H2-02 mixture would not logically require prior investigation of the HPNS effect relative to hydrogen. However, this would be anticipated to be a logical research requirement with respect to H2-He-02 mixtures. Further the possible desirability of using one mixture may be very high as opposed to the other under different operational conditions. As a result, it seems logical to make two different sets of research recommendations. One for H2-02 mixtures and the other for H2-He-02 mixtures and the proposed areas and operational applications would likewise be identifiable as to the mixture in question.

Another interesting question deals with the ultimate depth of application (which is greatly different between the two mixtures). Air mixtures have been routinely utilized in diving for hundreds of years. Although much research is helpful to increase diver safety and expand potential use of this mixture, it could be fairly argued that further physiological research is not a pre-requirement for continued use of air diving within the presently established range of application. If, however, one desired to utilize air dives to 100 meters certain research would be required in the areas of narcosis, narcotic adaptation, decompression table development, etc. Research requirements prior to utilization of H2-02 and H2-He-02 mixtures may vary greatly depending upon the proposed maximum depth of application. As a result, this report identifies two depth ranges for each mixture. The lower one would be achieved with presumably much less research effort than the higher and hence achieve operational utilization status (if and when desired) at a much earlier date.

As an example, there appears to be some disturbing aspects with respect to hydrogen narcosis which should be thoroughly investigated before a maximum depth of 250 meters could be utilized. However, in view of the past experiment evidence, it might be possible to utilize hydrogen to a depth of 150 meters with little additional research required in this area.

As a result, recommendations for hydrogen/helium/oxygen mixture will be made for maximum depth ranges of 450 and for depths in excess of 450 meters. For hydrogen-oxygen mixtures, recommendations will be made for maximum depth ranges 150 meters and depths in excess of 150 meters.

Finally, it is hoped to identify potential areas of application with both mixtures where such usage would provide a reasonable alternative to presently used mixtures or would have especially advantageous characteristics as compared with mixtures presently in use.

NARCOSIS/HPNS BALANCE

Initial results of the Hydra V experiments indicated the effectiveness of hydrogen to balance the pressure reversal effect and it appears that this depth could be attained in practice with only minimal additional verification of the percentage of hydrogen required to provide an optimum balance. The ultimate depth of application may depend upon the relative slope of the pressure reversal effect. At very deep levels the degree of freedom of the percentage range of hydrogen in a mixture to counteract the pressure reversal effect may become progressively more restrictive and require more extensive research to determine the relative effects and to titrate the mixture to achieve a physiologically tolerable balance between these effects. A multi-level experiment in which the hydrogen percentage was varied between the onset of HPNS symptoms and narcosis could serve to indicate the optimum ratios as the range is varied and also the variation, if any, in the "bandwidth" of permissable variation in the percentage as depth is increased. It is suggested that research in this area be considered essential if development of diving capability with $H_2/He/O_2$ mixtures is contemplated below 450 meters.

Both human and animal studies (at higher pressures) would be recommended. Obviously, this is not an applicable requirement for H_2-O_2 mixtures alone.

NARCOSIS

The experience indicates that narcosis would not be a problem with dives up to a depth of 150 meters. Indeed this is somewhat more conservative than the evaluation of Dr. Fructus (9) with much more first hand experience with this problem.

If diving below 150 meters with H_2-O_2 mixtures is to be achieved, one must be concerned with the effects of narcosis as such. Concern should be given not only to the intensity of the narcotic effect but as to the "type" of narcotic effect as well. Indeed that latter may be more important than the former. In both the French and Swedish experiments, the subjects reported a distinct difference in the type of narcosis symptoms experienced with hydrogen as compared with nitrogen. Reported symptoms with hydrogen included alteration of their perception of light levels and spectral shift, hypersensitivity of hearing and touch, disorientation and vertigo, interior dialogue, sensory and somesthetic hallucinations and what he describes as the "superman syndrome" (an exaggerated assessment of capabilities).

Some effects, such as the superman syndrome, could be potentially life threathening under certain conditions where an exaggerated assessment of a diver's capabilities results in his taking an action which would be considered unsafe by the same man under normal circumstances.

Dr. Fructus (28) also noted that the symptoms often persisted for considerable periods of time after the breathing of hydrogen-oxygen had been discontinued.

It is interesting to speculate as to whether this is a different form of narcosis or merely a different manifestation of narcosis because of application under unusual conditions. In any case the lack of knowledge of the effects with hydrogen and the limited experience to date with hydrogen narcosis would suggest that further investigation into this area be of prime concern for possible future dives with hydrogen-oxygen below 150 meters.

Although the narcotic effect of hydrogen is balanced by the pressure reversal effect at greater depths where $H_2/He/O_2$ mixtures are utilized, the lack of sufficient experiments, at this time, to provide a complete assurance regarding the precise percentages of hydrogen which may be safely utilized in a multi-inert mixture at various depths, suggests a high priority for this research area for multi-inert dives below 450 meters also.

While animal experiments have been useful in determining the relative narcotic effect of hydrogen it is doubtful that they could contribute much more with regards to the apparent differences in symptoms presented.

RESPIRATORY DEPRESSANT EFFECTS

No respiratory problems were evident under conditions in which the hydrogen partial pressure was within acceptable limits with respect to narcosis. However, the respiratory depressant effect on one subject breathing hydrogen at 240 meters in Hydra IV, Imbert (30), suggests some potential problem areas.

At the end of 5 minutes, some disorganization of the ventilatory rhythm was observed in some subjects and on one subject b came very slow by the end of the 6th minute and necessitated the ter .nation of the hydrogen inhalation period. The phenomenon seemed readi' reversible once the subject's breathing mixture was switched to h ium-oxygen. However, it strongly suggests the need for further stud (animal and human) to determine the cause and conditions which must .e applied to avoid this problem.

It was noted that the mean oxygen consumptic during exercise at 240 meters was significantly lower on Hydrox as opposed to Heliox. This suggests possible problems which could result from CO2 retention, Lanphier (31), similar to those previously experienced with nitrogen-oxygen breathing mixtures at elevated pressures. A respiratory depressant effect has also recently been observed as well as with the xenon breathing protocol used for blood flow study (at surface pressure), Winkler (32). Research in this area must be highly recommended prior to any proposed operational utilization of hydrogen in the narcotic range with H2-O2 or H2-He-O2 mixtures.

DECOMPRESSION (SLOW TISSUE COMPARTMENTS)

Interesting enough, only Edel (6,7,15) and Fife (14) have made studies in which decompression was a primary interest. In other studies decompression requirements were assumed to be within certain limits and in general the studies utilized tables which were believed to be within safe limits. The lack of symptomatic response to decompression in recent French and Swedish studies in which the slowest tissue compartment was controlling, attests to the safety of the procedures followed.

The practice of linearization for convenient control in saturation decompression, lack of DCS problems, and lack of knowledge of the individual base susceptability to decompression sickness of the divers, precludes a meaningful evaluation of the decompression profiles in terms of the decompression obligation in the slowest tissues from the most recent saturation exposures.

With respect to the slowest tissue compartments, the results of Project Hydrox II, Edel (15) appears to provide the most definitive information with respect to decompression obligation. In this study the same subjects were exposed to two hour exposures at 200 FSW with normoxic mixtures of nitrogen, helium, and hydrogen in separate dives spaced one week apart to avoid influence from acclimatization. Analysis of the data (which involved a 50% incidence of sickness for each mixture used) indicated that the decompression requirements for hydrogen were almost exactly midway between that for helium and nitrogen for the slowest tissue compartments.

In terms of research requirements, the problem is somewhat academic. Saturation decompression, utilizing linearized ascents, is a much simplier problem than that for "bounce" dives in which many tissue half-time compartments are involved and the staging must be optimized for a decompression procedure which is both rapid and safe. In a saturation decompression profile only one compartment is involved and an additional decompression time of 10 or 20 percent (after weeks of exposure at the working level) if of little consequence. In a specific instance, it is always possible to reduce the ascent rate for an occasional problem with a more susceptable individual.

The practical results from the recent Swedish and French experiments indicate the ability to provide for safe decompression from such saturation exposures. While further verification of the ascent requirements is desirable, this can be done as a part of a necessary experiment.

Excursions from a saturation base present a greater problem. However, if the same gas mixture is utilized for both the saturation and the excursion present data should be sufficient to provide adequate excursion limits and verification of sample excursion profiles could be accomplished as an adjunctive study to other primary experimental research programs with hydrogen.

DECOMPRESSION (FAST AND INTERMEDIATE TISSUE COMPARTMENTS)

In this area little available data exists. Some information is included in studies by Edel (6,7) and Fife (14) but is insufficient to provide verification of a decompression model for hydrogen. On the positive side many of the profiles were successful with the limited number of subjects utilized in the programs. In Project Hydrox II, the only incidence of decompression sickness occured in the slower tissue compartments which were being studied and as a result of reductions of the anticipated decompression requirements for those tissue compartments. In this study, most of the faster tissue compartments were not involved in the decompression requirements and care was taken to assure that the early portion of the decompression, where faster tissue componants were involved, was overly conservative so as not to influence the result of the study of the slowest tissue compartments.

Both Edel and Fife experienced problems related to the faster tissue compartments. In some cases the decompression requirement for hydrogen in the faster tissue compartments seemed to be unusually restrictive, in consideration to an anticipated range of half-time and M-values, when compared with the decompression requirements for the same compartments for nitrogen and helium. An accurate knowledge of the decompression requirements for such tissue compartments would be essential for the development of decompression tables for use with hydrogen-oxygen mixtures in a bounce diving mode.

Animal studies unfortunately do not provide the definition required in this case. However, it would appear that such studies with human subjects would be required as a prerequisite to possible future of hydrogen-oxygen mixtures.

TABLE DEVELOPMENT

Some table development is required based upon above recommended studies. For reasons previously stated this would be a comparatively more involved effort for hydrogen-oxygen bounce dives than for the use of H2/He/02 mixtures as such.

COUNTERDIFFUSION STUDIES

Some animal studies, D. Aoust (33) indicated no anticipated problems should result from isobaric switches between helium and hydrogen in either direction. Recent experience with the Comex experiments on Hydra IV and Hydra V indicate that this is not applicable to humans.

Fructus (28) has demonstrated that although rapid shifts from prolonged exposures at high pressures with hydrogen-helium-oxygen mixtures to helium-oxygen can provoke problems as a result of counter-diffusion, a gradual change of gas mixtures over a prolonged period is safe. If the latter procedure is adopted as practice, counterdiffusion studies would be of less importance. However, some assurance would be desired as to the safe envelope which would apply to such shifts. As a result, conterdiffusion studies for H2-He-02 mixtures would seem highly desirable, in both animal and human studies although past experience in decompression studies in general indicates that animal data must be evaluated very cautiously when considering human responses.

With relation to hydrogen-oxygen mixtures the situation is more complex. Because of the flammability limits hydrogen-oxygen mixtures cannot be utilized much below 200 FSW. This requires other gas mixtures to be required during the descent and subsequent decompression. In commercial dives gas switches between nitrogen-oxygen and helium-oxygen mixtures are made routinely. Such practices have been utilized operationally for many years without problems.

However, the dives are programed so that such gas shifts are only made in the safe direction with respect to counterdiffusion or at times in which the reverse gas switch takes place (from nitrogen to helium) is accomplished during the initial portion of the profile when the diver is descending and an insufficient quantity of helium exists in the tissues to cause problems.

With hydrogen-oxygen mixtures, a limitation is applied with respect to the minimum depth in which the gas may be safely utilized. As a result the gas switches must be programed around this problem. A direct switch to a helium-oxygen mixture during decompression following a hydrogen-oxygen exposure would be extremely likely to provoke serious problems. A switch could be made from hydrogen to nitrogen but in many cases this would occur close to 200 FSW and switching from helium to nitrogen at depth deeper than 150 FSW has been found to provoke decompression problems in commercial diving operations.

A method is theoretically possible to make such a shift using a helium-nitrogen-oxygen mixture according to the Autodec III model, this however would need to be verified in practice. Admittedly, the problem did not exist in Project Hydrox I & II studies. However, in those cases the profiles were designed to make hyperbaric exposures in which the gas switches could be made under conditions which would be permitted under the theoretical counterdiffusion model used. A more comprehensive use of this gas mixture would involve other cases in which such methods could not be applied.

The remaining option would be to do studies of counterdiffusion which would result in a more accurate assessment of the safe envelope in which such gas shifts can be safely achieved.

SPEECH

Aside from the Comex V experiments (the results of which are not available at this time) the only comparative study of the divers speech was made by Seargent (16) in connection with the Hydrox II project.

In this study, speech samples were made of the divers at 200 FSW breathing normoxic mixtures of nitrogen, helium and hydrogen (as well as air at surface pressure). As a result of these studies he concluded that there was not significant difference between intelligibility in hydrogen as compared to helium.

Communications has always been a problem with respect to diving operation and particularly so when the diver is breathing mixtures such as heliox or hydrox. In view of the above study, however, the use of hydrogen does not produce any additional problems in this regard and hence would not be a logical research prerequisite for use of these mixtures.

PULMONARY STUDIES

All studies to date have indicated no problems with respect to hydrogen. If anything, the studies have shown lower breathing resistance, and increased flow rates with hydrogen. While such studies are valuable in their own right and would be desirable, when possible in future experiments, they do not appear to indicate a prerequisite study for hydrogen utilization in general.

However, such studies would be necessary as a part of future studies of the observed respiratory depressant effects and would be recommended as a adjunct to any future studies of hydrogen-oxygen at pressures beyond those presently achieved by Comex.

BIOCHEMICAL & RELATED STUDIES

Aside from the experiments reported by Michaud, et al (18), all results with hydrogen have been most notable by the absence of contraindications to use of such mixtures. In retrospect, most authorities appear to agree that the problems encountered in the above report was due to experimental problems (possibly inappropriate temperature control or contaminants in the breathing mixture) not related to hydrogen. Aside from a logical requirement to make further studies when more adverse conditions would be applied in hydrogen oxygen experiments, such as at increased pressure, no need for further studies is apparent.

THERMAL EFFECTS

Although it is suggested by Smith (34) that thermal problems with hydrogen, specifically respiratory heat loss, would be more severe with hydrogen than with helium only one animal experiment reported by Michaud et al (18) might have involved thermal effects. If so, it could be argued that the same results would have applied whether the environmental gas was helium or hydrogen. All other animal and human experiments were without any problems related to thermal effects, Adequate control of the environmental gas temperature or compensatory measures are essential for any highly thermal conductive gas (or liquid) involved. Experience has indicated that the same type of systems that are applied to helium can also be applied to hydrogen mixtures with slight modification.

A more critical factor would be the diver's ability to perceive a condition of thermal imbalance and the effects of narcosis in altering this perception. This, however, is more properly related to narcosis studies as such.

The recommendations for areas of further research are summarized in Table I. In this table the distinction between H2/He/02 mixtures and hydrogen-oxygen mixtures is preserved and further distinction is made by the supposition of a limited maximum depth as opposed to exposures beyond this range.

TABLE I

RECOMMENDED RESEARCH AREAS FOR H2-02 MIXTURES

	H2-02 MIXTURES TO				**H2-He-02 MIXTURES TO**			
	150 Meters		**150-250 Meters**		**500 Meters**		**Over 500 Meters**	
RESEARCH CATEGORY	**Animal**	**Human**	**Animal**	**Human**	**Animal**	**Human**	**Animal**	**Human**
HPNS/NARCOSIS BALANCE						B		A
NARCOSIS		C		A		B		A
RESP. DEPRESSION Eff.		C	A	A		B	A	A
DECOMPRESSION SLOW T				B		C		C
DECOMPRESSION FAST T		A		A				

RESEARCH CATEGORY	H_2-O_2 MIXTURES TO 150 Meters Animal	150 Meters Human	150-250 Meters Animal	150-250 Meters Human	H_2-He-O_2 MIXTURES TO 500 Meters Animal	500 Meters Human	Over 500 Meters Animal	Over 500 Meters Human
COUNTER DIFFUSION		A	B	A		A	B	A
BIOCHEMICAL							A	A
PULMONARY								A
PERFORMANCE STUDIES				C			A	A
SPEECH								
THERMAL EFFECTS				C				C
TABLE DEVELOPMENT		A		A		C		C

A. Essential research area

B. Highly desirable research area.

C. Recommended as an adjuntive study to programs of primary interest.

APPLICATION TO DIVING OPERATIONS

Although physiological requirements of a breathing mixture are extremely important, other factors also need to be considered.

If a breathing mixture were ideal in all respects, but supply of such a mixture was as rare and costly as radon, such a mixture would probably never be utilized beyond the confinements of a laboratory. In terms of cost, helium is within the acceptable range for use near countries which produce this gas. However, in some parts of the world (Southern Africa, Southern areas of South America, Australia and Alaska) problems involved in transportation of this gas may bring the base price to over 10 times the cost in the U. S. Commercially, the cost in such areas is sufficiently high to warrant development of alternate breathing mixtures. Further, the world supply of helium is being depleted and some estimates are that 15 years from now the available supply will be drastically reduced (35). The helium that might be obtainable would logically be tied to the law of supply and demand with prices for helium that would make it impractical as a breathing medium.

Another problem well known to commercial and military diving experts is related to supply problems for the breathing mixtures. Air diving only requires a compressor to provide for all the needs of a diving operation. Helium on the other hand must be either carried on board or resupplied at intervals corresponding with the use of the gas. Because of the large volumes of gas required, large amounts of valuable space aboard diving vessels are utilized for gas storage. Even with the allotment of such space, large scale commercial diving operations normally require resupply of breathing mixtures at weekly intervals. While such problems are acceptable for diving in the Northern Hemisphere, the volumes required present a logistical nightmare for operations in the Southern Hemisphere.

For a breathing mixture to be ideal in the practical sense, it should be available on (or near) the diving site, and within reasonable cost.

Most hydrogen-oxygen experiments have utilized pre-mixed supplies of the gas. Gas suppliers have blended stocks of hydrogen and oxygen (obtained by various commercial methods) to the required percentage, Edel (36). While this is satisfactory for a limited series of experiments, it presents essentially the same problems presently existing with helium-oxygen mixtures. Arny Zettertrom (37) realized the value of being able to manufacture the gas aboard the diving vessel and designed a system whereby a mixture of hydrogen-oxygen could be manufactured at sea from supplies of ammonia via the cracking process. Oxygen was added at a later stage to complete the mixture. While the system had some advantages, it was still necessary to have storage facilities for the ammonia and the resulting mixture had about 25% nitrogen which imposed a lower ultimate depth limit to the gas with respect to narcosis limitations.

An additional potential problem is encountered in the final oxygen addition. Hydrogen and oxygen are explosive over the vast majority of the mixing range. To develop a mixture which is non-explosive and non-flammable not more than 4% oxygen in hydrogen may be permitted. In a "topping off" process one must have an explosive mixture at the interface of the gases. Not until the mixing process is completed and mutual diffusion completed can the supply be considered "safe".

It would, however, be technically feasible to generate hydrogen-oxygen mixtures in a pure form by electrolytic separation from sea water. This would make any such diving operation above 200 meters independent of a shore based supply.

In 1982, an inhouse conceptual study was made of a shipboard system for safely generating hydrogen-oxygen mixtures from sea water. Such a system would eliminate the present supply and storage problems presently associated with helium-oxygen diving.

Hydrogen-oxygen then may have several advantages for general diving operations, in comparison with helium-oxygen, from both physiological and operational viewpoints. In some specialized applications requiring exposure to very high pressures or independence from shore based supplies it may be the only gas (alone or in combination with helium) to provide a satisfactory breathing media for hyperbaric exposures. Further, the depletion of the worlds helium supply may leave hydrogen as the only inert which can be reasonably available for deep bounce dives at some point in the foreseeable future. Hence an evaluation of the application of hydrogen could have some importance for future diving operations.

The use of helium-oxygen offers many complications in contrast to air in diving. As a result, this gas is used in practical operations only when the operational requirements of a diving operation are such that the limitations of air diving are outweighed by the advantages of the more complex helium-oxygen systems. Hydrogen-oxygen and hydrogen-helium-oxygen systems add still more complications over the use of helium-oxygen and hence would not be expected to be utilized except when the advantages clearly outweigh the added complexity as compared with helium-oxygen systems.

In general the added problems of utilizing hydrogen-oxygen are:

1. Precautions required with respect to flammability/ explosive limits.

2. Added instrumentation and operational procedures to be followed.

3. Requirements for shifting of breathing mixtures and/or environmental gases.

4. Restrictions with respect to minimum depth utilization of mixtures.

5. Increase of decompression time as compared with helium-oxygen.

The indicated areas of advantage are:

1. Indicated possible increased depth capability.

2. Reduction of breathing resistance and probable increase in divers performance.

3. Availability of principal gas mixture as compared with helium.

4. Reduced cost of principal gas mixture as compared with helium.

5. Ability to be independent of shore based supplies by on board mixing capability.

6. Possible reduction of on board gas storage requirements by on board mixing capability.

Air diving provides an adequate breathing mixture within the 0-150 FSW range and can be applied between 150-200 FSW range with little problem for dives of limited duration. Hence, it is doubtful that any mixture is likely to be substituted for air in the 0-150 FSW range and only in cases where prolonged exposure is involved in the 150-200 FSW range. The primary limitation is due to nitrogen narcosis and to some extent the decompression obligation in the slower tissue half-time compartments.

Helium-oxygen mixtures have been shown in practice to be advantageous in the 150-1000 FSW range and indications suggest some possible limited application in the 1000-1500 FSW range. The principal problems are due to HPNS and, at very high pressures, with respect to breathing resistance.

Where helium-oxygen is readily obtainable hydrogen-helium-oxygen mixtures would then have the greatest potential application in depths below 1500 FSW and to some extent (where increased diver performance is required) below 1000 FSW. As the added complexities of using a hydrogen-helium-oxygen mixture are relatively small in comparison with respect to the probable decrement in diver performance in the 1000 to 1500 FSW range and an operation requiring operations at such depths would be anticipated to be fairly important to warrant the extensive equipment and personnel required for such a task, the physiological advantages of a hydrogen-helium-oxygen mixture would be likely to outweigh the disadvantages of some additional complexity of operation in most cases.

Beyond this the application of hydrox mixtures in general is likely to be based upon availability and supply problems with helium--oxygen.

For operations in or near U.S. coastal waters, in a depth range of 150 to 1000 FSW Helium-oxygen mixtures offer sufficient advantages of simplicity of operation to be the indicated mixture of choice. At greater distances, the advantages would still be valid for very limited operations where the amount of helium required would fall within reasonable storage limits and resupply of the gas mixtures would not be required. For more extensive operations away from the immediate vicinity of the U. S. coastal waters, a hydrogen-oxygen or hydrogen-helium-oxygen system, utilizing on board mixing capabilities would appear to offer the best possible solution to achieving required underwater tasks.

RECOMMENDATIONS AND CONCLUSIONS

1. Hydrogen-oxygen mixtures have shown sufficient advantage to warrant further research for possible future applications.

2. Present experience indicates that H2-02 mixtures offer some potential advantages over present helium-oxygen bounce diving applications for operations where on site gas storage space is limited and/or resupply of breathing gas mixtures are a potential problem.

3. Present experience indicates that H2-He-02 mixtures offer some potential advantages over present helium-oxygen saturation diving operations at depths where increased diver performance and reduction of breathing resistance is an important factor.

4. Hydrogen narcosis effects and decompression requirements are the major primary physiological research areas requiring investigation prior to possible applications of such mixtures for operational usage.

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